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By

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Assistant Chief of Aerodynamics
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DOUGLAS AIRCRAFT COMPANY, INC.
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For presentation at the
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FLIGHT CHARACTERISTICS OF THE DC-8

By

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INTRODUCTION

When the modern high speed swept wing jet transports were first introduced into airline service, there followed many articles and papers discussing the characteristics of the new breed. Terms like "these jets" and the "typical jet transport" led everyone to believe that all the new jet transports were alike. From the passenger's point of view, they were all pictured as the ultimate in smooth fast air travel, while from the pilot's standpoint, they were all described as having certain inherent and rather discomforting flight characteristics. Now, some of this generalization was true; at least they were all fast, quiet, and comfortable, but in the flight characteristics department, they were not all the same. In fact, we don't think the DC-8 fits the initial picture of the "typical jet transport" at all as far the flight characteristics go. We believe that the DC-8 represented a significant step forward in the state of the art of flight characteristics on large swept wing jets, and that it is of general interest to review briefly just how that step was made.

It is the aim of this paper not simply to describe typical flying qualities but rather to summarize the key design concepts and engineering developments which have resulted in the excellent flight characteristics of the DC-8 jet transport.

THE DESIGN PROGRAM

Ground Rules

The machine pictured in Figure I is the result of nearly ten years of design effort, the last four involving the detail design, construction, and flight testing of the production configuration laid down on the drawing boards late in 1955. Before discussing technical design problems, three important ground rules which governed the design of the airplane should be stated.

Since a prototype was not to be built, the airplane must be designed for production but with margins to handle all foreseeable problem areas. This rule is of paramount importance if the benefits of by-passing a long prototype development program are to be realized.

The second ground rule was simply that the flying qualities must not be sacrificed for performance benefits. This rule imposed some extremely difficult design problems, since the flying qualities standards for the DC-8 were higher than the excellent standards met by previous Douglas transports.

The third ground rule was that no single failure of any component should jeopardize the safety of the airplane. This is the fail-safe concept embodied in all Douglas commercial transport designs.

Wing Design

When work was started in 1951, jet transport cruise requirements and the state of the art dictated a relatively thin wing of approximately

thirty-five degrees of sweep. Because of the aerodynamic, structural, and dynamic difficulties associated with such a wing, Douglas development effort was directed toward achieving the desired cruise Mach number with minimum sweep and maximum thickness.

At the outset, it appeared that only modest decreases in sweep would be possible, and thirty degrees was chosen as the desired goal. Efforts were then directed toward the development of airfoils to satisfy the design requirements. In this work we drew heavily on our ten-year background of airfoil development.

Many conventional high-speed airfoil sections were found to provide the required high-speed performance but they had relatively poor maximum lift capability. Even for straight wings these airfoils were woefully deficient, and the effects of wing sweep only compounded the problem as shown in Figures 2 and 3.

Typical spanwise lift distributions at high angles of attack for a straight and a swept wing are shown in Figure 2. The dashed line, to which both the curves are tangent at some point, shows the usual distribution of airfoil maximum lift capability along the span. Because the swept wing loads up more rapidly near the tip, and because practical amounts of washout are ineffective in eliminating this condition, a conventionally designed swept wing will exhibit tip stall. This leads not only to a complete loss of lateral control in the stall, but also to a violent pitch-up.

One solution to the swept wing stall problem is achieved by lowering the lift capability of the inboard wing sections to insure that this area stalls first. Such a revised lift capability distribution is shown in Figure 3. This soltuion has not been generally acceptable in the past because of the large loss in wing maximum lift capability.

On the DC-8, however, it became possible to use this method to solve the tip stall problem when our research efforts developed a high drag divergence Mach number airfoil for the outer panel which had even higher than normal maximum lift capability. (Indeed, the airfoils used over the outer panel of the DC-8 have higher $C_{L_{max}}$'s than any good conventional airfoil in use today.) With these high-lift outer panel airfoils, the required reduction in inboard airfoil maximum lift capability can be made without unduly compromising the total wing maximum lift. Thus, the DC-8 wing is defined by three airfoil sections. These airfoils are located as shown in Figure 4. (The designation "DSMA" stands for Douglas Santa Monica Airfoil, and the number following the dash is the airfoil design number. Thus, the outer panel airfoils are the 87th and 88th of the design series for this job. The inboard airfoil is the 128th airfoil designed in this series.) DSMA 87 and 88, which define the outer panel sections, are the airfoils having the extremely high lift capability in combination with a high drag divergence Mach number.

Figure 5 shows DSMA 87, the mid-semispan station. It is characterized by a relatively flat top in the crestline area and a blunt leading edge. This airfoil is 10.2 percent thick. The inboard airfoil which controls the stall could have been a sharper nosed version of DSMA-87 if it weren't for the root interference effects, particularly at high Mach number. These result in a loss of effective sweep and an increase in aerodynamic camber. The inboard airfoil was designed to cancel these adverse effects as well as to control the stall. This leads to its somewhat unconventional appearance as shown in Figure 6.

The resulting DC-8 wing, designed according to these concepts, did indeed meet the requirements laid down for it. It had the desired high drag divergence Mach number, good maximum lift capability, and stall characteristics essentially the same as those of a straight wing.

If this were the whole story, further design work would have been unnecessary. However, the DC-8 was designed to always operate with nacelles and pylons attached to the wing. The adverse high-speed interference effects of these appendages were eliminated through careful design which included cambering the pylon. Their mitigating effect on the stall characteristics of conventional swept wings was still in evidence, however, and the $C_{L_{max}}$ loss associated with these pylon effects nullified much of the $C_{L_{max}}$ gain inherent in the basic wing.

Since the help of nacelles and pylons was not required to attain good stall characteristics, a considerable amount of research and development effort was put into eliminating this adverse lift effect. Basically, the goal was to achieve as high a maximum lift for the airplane as was obtained for the plain wing without nacelles and pylons.

Of the many modifications examined both in the wind tunnel and by analysis, the most successful solution to the problem was the incorporation of wing leading-edge slots just inboard of each wing-pylon intersection. Figure 7 shows the initial test configuration installed early in the DC-8 flight program. The production airplanes have inboard slots approximately 40 percent of the span shown.

The leading edge slots are open only when the flaps are deflected. With flaps up, the slots are sealed off on both the upper and lower surfaces by flush doors. With slots open, the stall characteristics are essentially those of the basic wing.

That the desired goals have been reached is evidenced both by inflight tuft studies and by the stall characteristics themselves. There is no tendency to dig in or pitch up as the stall approaches. The full stall is characterized by a positive pitch down, even with full up-elevator, with little or no roll. Recovery is prompt, requiring no special technique to minimize the altitude loss.

Horizontal Tail

Great care was taken in the design of the horizontal surface, both as to configuration and placement on the fuselage to minimize any adverse compressibility effects. The design philosophy was simply that of making the tail less critical than the wing. This surface is swept thirty-five degrees, five degrees more than the wing, and utilizes special Douglas airfoils. It is placed at the extreme rear end of the fuselage where the velocities are less than freestream. Longitudinal trim is accomplished by an adjustable stabilizer. A relatively small chord elevator is used to preclude adverse hinge moment effects at high Mach number.

The elevator is equipped with an elliptical nose overhang balance of approximately 35 percent chord. The success of this balance type at high Mach number is illustrated in Figure 8. Here are shown typical elevator hinge moment characteristics at both low and high Mach number. It can be seen that at an airplane Mach number of .96 there is essentially no change in the hinge moment characteristics from those shown at a Mach number of .2. Each of the curves covers an elevator and tab deflection range of interest for the corresponding Mach number of operation. These characteristics have been verified by F.A.A. dive tests to a true Mach number of .97 on the Askania Tracking Range of the Air Force Flight Test Center at Edwards Air Force Base.

As originally conceived, the elevator was aerodynamically driven with a single long span control tab on each elevator. A zero link ratio or pure flying tab control system was utilized with suitable springs incorporated. One was between the elevator and the tab to minimize the undesirable free-floating tendency of the elevator when the airplane was on the ground. Early flutter analyses, however, indicated that the long span free tab detrimentally affected flutter characteristics and could not be tolerated. Since a smaller control tab would not drive the elevator to full travel under critical control conditions, some other solution had to be found.

The answer turned out to be quite simple. The tab was split in two pieces. The inboard section was retained as the control tab and the mechanical advantage over this tab was cut in half. Reducing the mechanical advantage retained the original aerodynamic force levels at the cockpit developed by the larger one-piece tab, and at the same time converted the system to a linked tab control wherein the pilot has control over both the tab and the main surface. As a consequence, the control system could be simplified and the tab-to-elevator ground control spring eliminated. To retain the desired control capability, the outer piece of the original control tab was converted to a geared tab with a motion which approximately matched the motion of the original control tab under the critical maneuvering conditions. The resulting configuration has been highly successful from the start. The only changes made since first flight were minor ones to the control column centering spring during adjustment of the Mach trim compensator to properly mask the transonic tuck.

Typical transonic tuck characteristics for the DC-8 at high altitude and high gross weight are shown in Figure 9. The tuck is mild and allows the use of what we believe is a simpler, safer Mach trim compensator concept. This device cancels the trim change effect by an automatic feedback from a spring rather than by repositioning the stabilizer as a function of Mach number. A runaway failure of such a device can produce no more trim change force than the maximum built into the spring system initially. This Mach trim compensator is a simple fail-safe system.

Vertical Surface

Swept wing aircraft require large span vertical surfaces to counteract the adverse effects of sweep and provide satisfactory Dutch roll characteristics and the DC-8 is no exception. A large rudder is also required to handle the tremendous yawing moments developed by the jet engines in the event of an engine failure. The large vertical surface coupled with the lesser swept wing provides satisfactory inherent Dutch roll characteristics under all airplane operating conditions. Although not a requirement for certification, a yaw damper is provided as standard equipment on the DC-8 to heavily damp the Dutch roll under every conceivable condition. With the yaw damper operating, the Dutch roll damping is nearly dead beat.

The DC-8 vertical surface also provides the airplane with excellent crosswind landing capability and ease of control under asymmetric thrust conditions even with two engines out on one side. Landings in ninety degree crosswind components up to 34 knots have been demonstrated during the F.A.A. certification program. Air minimum control speeds are less than the lift-off speeds at all normal take-off gross weights. Directional trim for one-engine-out climbs is sufficient to allow wings-level climbs to be made with rudder (and aileron) forces trimmed to zero at all altitudes.

Because the swept wing and the high thrust levels of jet engines place severe demands on the directional controls, the DC-8 rudder was designed from the beginning to be fully power-operated. Light, comfortable forces (90 pounds maximum) are provided by a simple feel spring unit. In case of power failure, the rudder control system reverts automatically to a manual tab control system.

During his first flight in the DC-8 a few months ago, an experienced jet pilot inadvertently demonstrated the effectiveness of the large fully powered rudder. After a three-engine landing, made to acquaint him with the characteristics of the stand-by manual rudder and aileron systems, power was applied for the subsequent take-off. At V_1 an outboard engine was cut and at the critical moment of lift-off the Douglas pilot in the right seat cut the remaining engine on the same side. Rapid application of aileron and rudder control minimized the yaw transient and the airplane climbed steadily out on the two remaining engines. At this time, the literally "green" pilot easily turned into the two dead engines, circled the field, and landed again on the runway. What made this demonstration even more remarkable, however, was the fact that the entire maneuver was made on stand-by manual control!

Protection against catastrophe in such a maneuver lies in designing the vertical surface so it will not stall in the yaw transient following the cut of two engines on one side without pilot corrective action and then backing that up with an effective rudder and light rudder forces to minimize the change of ever getting into this predicament. For swept wing aircraft, a further design requirement is added. The lateral control system must be sufficiently powerful to counteract the large rolling moments developed at the excessive yaw angles produced in such a transient.

Lateral Controls

The large DC-8 rudder was demonstrated to provide excellent crosswind landing capability, but in so doing it introduced a lateral control problem. Figure 10 compares the rudder effectiveness in flight with that measured in the wind tunnel. It is seen that the flight and wind tunnel test data compare favorably. Figure 11 compares wind tunnel test and flight data showing the aileron angles required in sideslip. Here, the wind tunnel data were surprisingly optimistic. This figure also shows insufficient lateral control to be available to utilize the full effectiveness of the rudder. This was an intolerable situation. Although directional and longitudinal controls are attitude controls, and airplane's lateral control system is a rate control and it is imperative that rate control limits not be exceeded when the airplane is in equilibrium at its maximum attitude.

The excessive aileron deflection requirements indicated by the flight data implied either low aileron effectiveness or a higher wing dihedral effect than that shown in the wind tunnel. Study of related flight data resulted in the surprising conclusion that a higher

dihedral effect was responsible for the difficulty although the wind tunnel discrepancy has never been explained.

Changing the wing dihedral was obviously out of the question even though such a change would further improve the already adequate Dutch roll damping. More lateral control would have to be provided in some manner. Fortunately, it was a relatively simple matter to add a lateral control function to the ground spoilers. Figure 12 shows the large improvement in crosswind landing capability obtained. These spoilers function as a lateral control device only when the landing gear is down and when aileron deflections greater than half throw are required. This latter accounts for the break in the curve with spoilers operating.

Although the primary purpose of the spoilers was to make full use of the rudder capabilities in crosswind landing demonstrations, the obvious advantage of greater low-speed roll control was obtained. Figure 13 shows the measured roll rates at low speeds for the DC-8 with and without spoiler operation. Under these conditions, the DC-8 rate of roll at normal approach speeds is nearly twenty-five degrees per second. Even without the spoilers, the roll rates at normal approach speed are quite respectable for an airplane of this size.

The superiority of ailerons for lateral control near and at the stall is without question. Transport types, in particular, required good lateral control in this region. Spoiler controls have the advantage that they can be placed in the same spanwise position on the wing as that occupied by the wing flap. Since the more inboard position of any lateral control device is an advantage at extremely high dynamic pressure, due to the smaller losses associated with wing aeroelasticity, spoilers are advantageous at high speeds. With the successful development of the DC-8

stiffer wing of less sweep and with stall characteristics equal to those of a straight wing design, the use of the better aileron system for lateral control at all speeds became possible.

Since at least part of any lateral control system fulfilling the requirements of a swept wing jet transport must be power-operated, a full power system was chosen for the DC-8 aileron. A simple, efficient manual tab control is provided in case of hydraulic failure. This manual system, and a similar one on the rudder, is automatically engaged should hydraulic power fail. When on power control, the control tabs are locked at zero.

The DC-8 aileron incorporates a unique feature which improves the high-speed lateral control capability on either the power or manual systems. We call it the torque-coupled, split aileron. The aileron is divided into two sections. The outboard section is coupled to the inboard one through a preloaded torque link. The drive system is on the inboard aileron.

The operation of the torque-coupled, split aileron is quite simple. At low speeds, where the aerodynamic hinge moments are less than the torque preload, the two pieces operate as a single unit to provide a very powerful control device in this critical region. At high speed, on the other hand, the hinge moments on the outboard aileron exceed the preload at successively decreasing aileron deflections as speed is increased. Beyond this preload limit, the outer aileron ceases to deflect and the system approaches that of an inboard aileron control only. In this way, deleterious effects of aeroelasticity are minimized without the complication of shift-over or lock-out devices in the system.

Figure 14 shows the roll rates at high speed for several altitudes. At the maximum limit speed of the airplane, roll rates are

always equal to or greater than ten degrees per second. Although roll rates at dive speed could be less than this and still retain adequate control, the higher level was designed into the airplane as a precautionary measure should any undue characteristics develop at the high speed.

RECENT DESIGN DEVELOPMENTS

The basic DC-8 wing was designed for operation at lift coefficients of approximately .3. It was expected, and wind tunnel tests confirmed, that the variation of drag characteristics with Mach number at higher cruise lift coefficient would be small. Flight tests have verified the basic high-speed drag characteristics of the wing at lift coefficients of the order of .3; however, tests showed a higher than desired drag when operating at the higher lift coefficients corresponding to long range cruise conditions. Considerable development effort has been expended in reducing this high lift, high Mach number drag. At the same time, a general program of airplane clean-up was undertaken to eliminate or minimize every item of drag possible on the airplane. One of the changes made, for example, is the addition of the revised wing tips. Although it is rumored that we added these extended wing tips simply to change the DC-8 wing aspect ratio (it was 7.07), the real purpose of the tips is to alter the local flow effects which decrease the effective sweep at the tips. The resulting performance gain is twice that accounted for by the increase in aspect ratio alone.

The major result has been modification of the DC-8 airfoils at the leading edge. The original DC-8 airfoils were designed to allow quite high nose pressure peak when operating at high lift coefficients in the high Mach number, long range cruise condition. It was determined that the earlier drag rise at the high lift coefficients was associated with these nose pressures, and new leading edge shapes were designed. It was recognized that the airfoil modification would, of necessity, reduce the maximum lift capability of the airfoils. A small extension in

chord was therefore introduced to compensate for this lift loss. The new leading edge also required some redesign of the slots.

Flight tests have completely verified the improved characteristics of the wing with the new leading edge. There was a reduction in maximum lift capability of the airfoil sections but this was completely offset by the additive effects of the increased chord and the increased effectiveness of the revised slots. As a consequence, the new DC-8 wing has the same maximum lift capability as the original. The drag in the high lift coefficient region, however, has been significantly reduced.

Although this paper deals with flight characteristics, it may be interesting to discuss the airplane performance gain associated with the leading edge extension. The next slide illustrates that the revised leading edge reduced the drag at all lift coefficients; however, the most significant gains are at the higher long range cruise lift coefficients. The airplane performance gains associated with these drag reductions are dependent of course on 8 percent increase in specific range and a 2-1/4 percent reduction in operating costs. On extremely long range flights, or when strong headwinds require a reduction in payload, allowable payload may be increased by 7,000 pounds resulting in a 20 to 30 percent reduction in operating costs. Where range is not critical, the cruise Mach number can be increased by .02, without increasing fuel consumption, resulting in a 2 percent reduction in block time.

With the new leading edges, two flight characteristics have been significantly improved. The first of these is the buffet boundary. Figure 15 shows the flight-test determined buffet boundary of the DC-8

with the leading edge extension airfoils. At a representative gross weight and cruise altitude, the buffet onset occurs at a Mach number of approximately .88. The buffet builds up to a maximum intensity of approximately .92 and disappears almost completely at a Mach number of .94. The improved buffet characteristics raised the maneuver capability limits as well. For example, at the heavy weight, initial cruise condition, a 1.6g turn may be made at a Mach number of .82 before buffet onset is reached. The improved buffet boundary also allows the airplane to operate at altitudes approximately 2,000 feet higher without buffet than was originally possible. The additional air lane so obtained is extremely beneficial in the ever increasing crowdedness of today's air space.

The second beneficial effect of the revised leading edges has to do with the transonic tuck. A comparison of Figure 16 with Figure 9 shows that the already mild transonic tuck has been reduced to two-thirds of the force levels shown originally. Although the transonic tuck has never been a problem on the DC-8, the milder characteristics exhibited for the wing the the revised airfoils allow further simplification of the Mach trim compensator system. With this new leading edge, the DC-8 has the distinction of being the fastest intercontinental jet transport of the day.

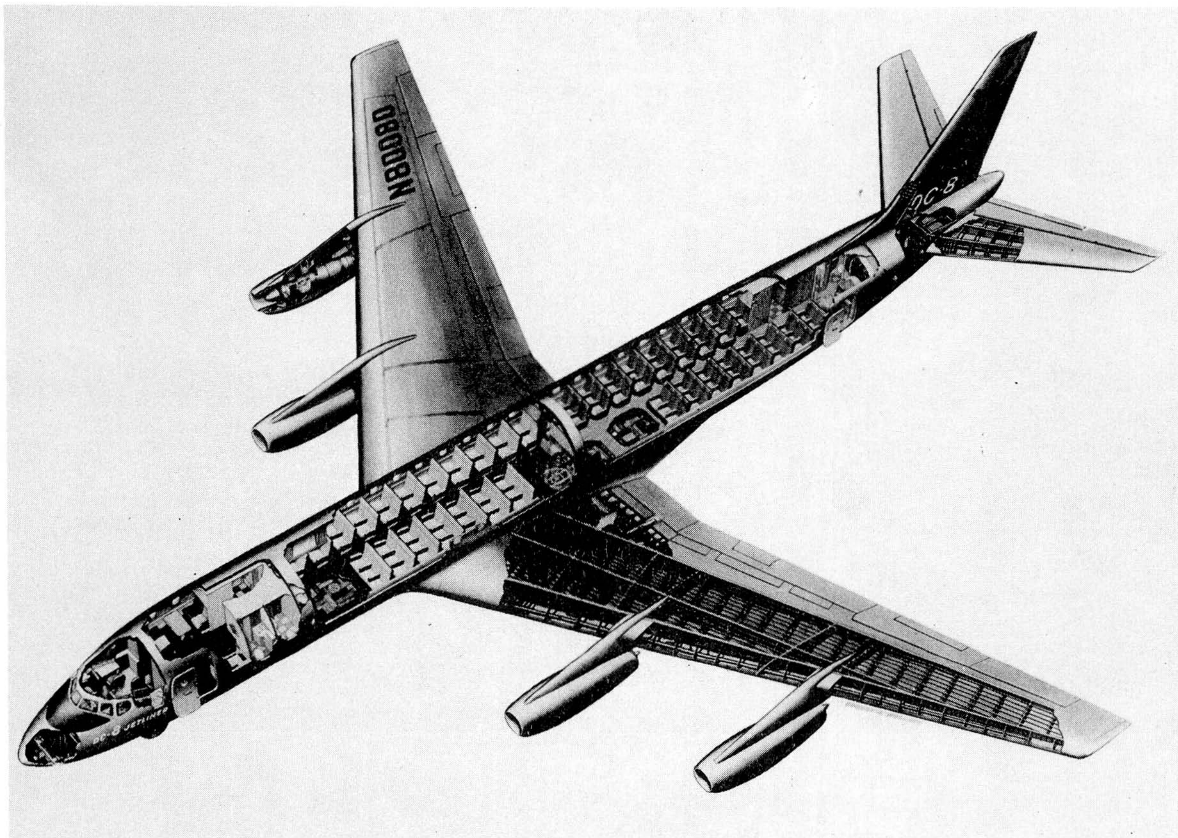

Fig. 1 Cutaway View of the DC-8

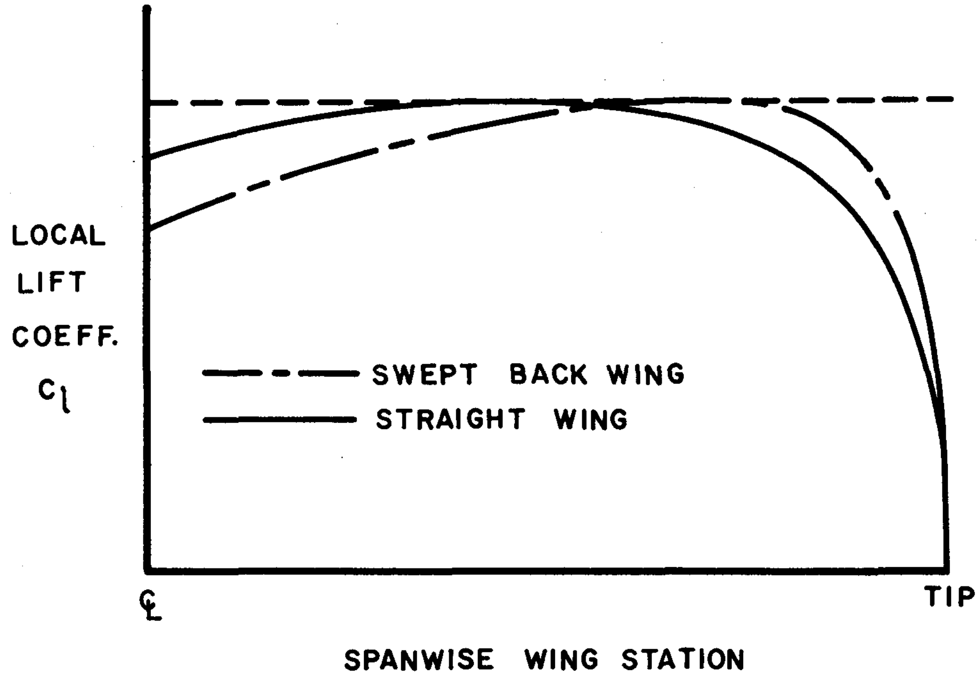

Fig. 2 Typical Spanwise Lift Distributions - Conventional Design Practice

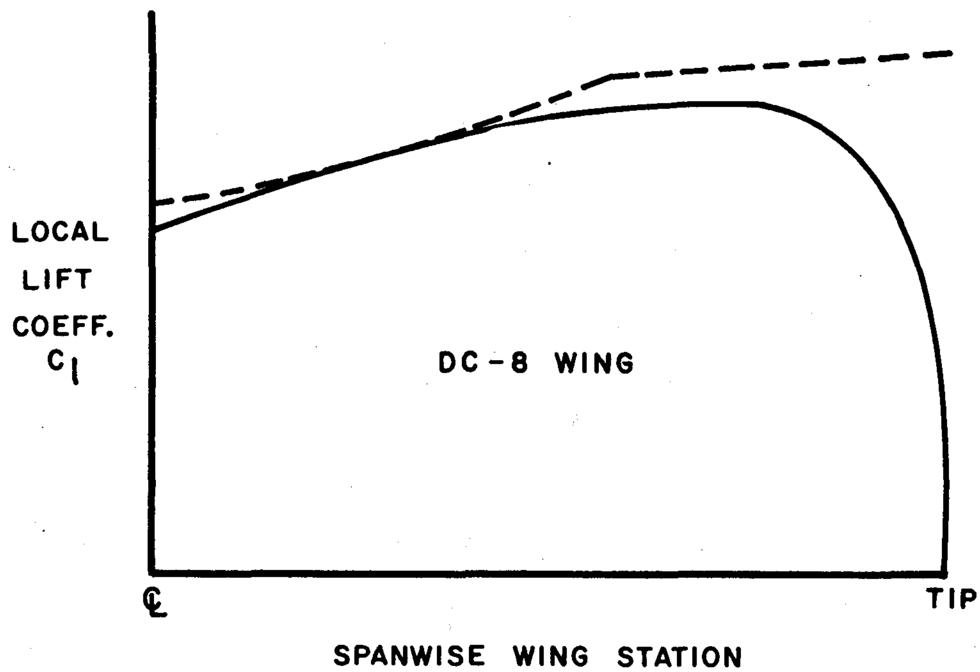

Fig. 3 Spanwise Lift Distribution - DC-8 Design Concept

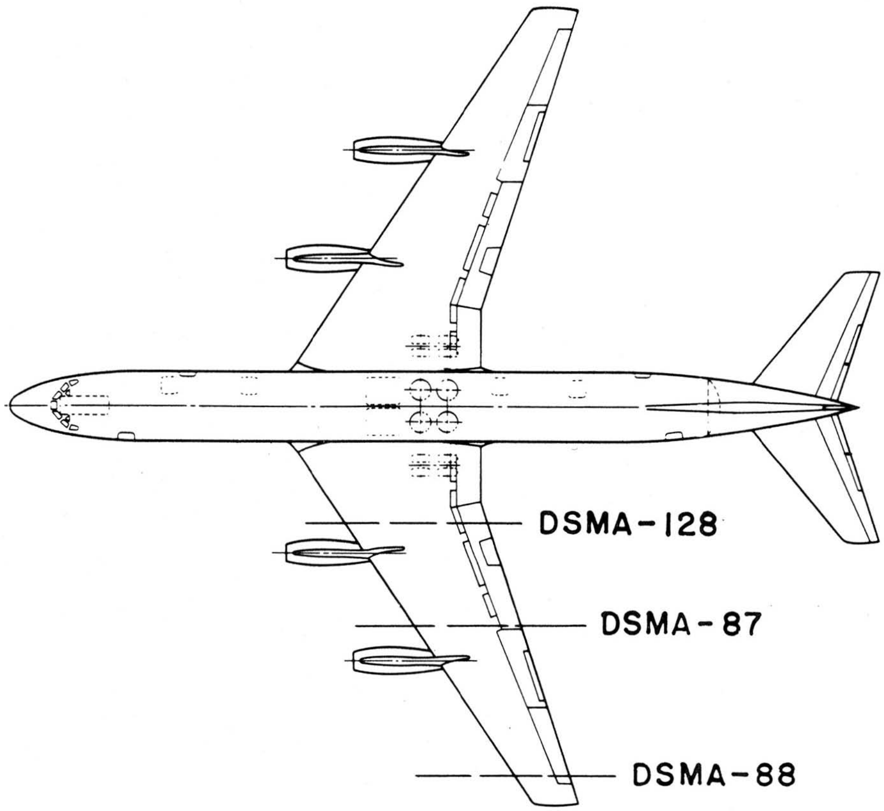

Fig. 4 Location of DC-8 Wing Airfoils

DSMA-87

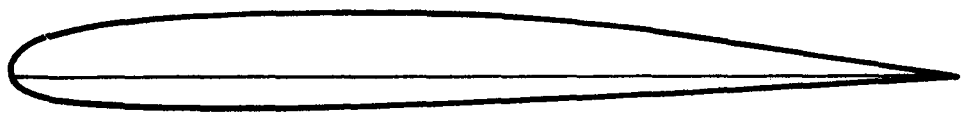

Fig. 5   DC-8 Wing Mid-Semispan Airfoil

DSMA-128

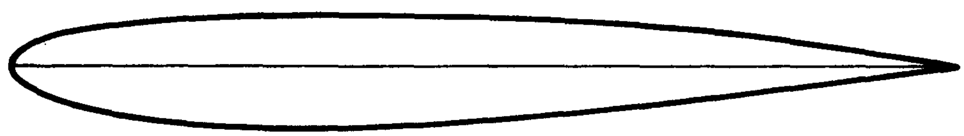

Fig. 6   DC-8 Wing Inboard Airfoil

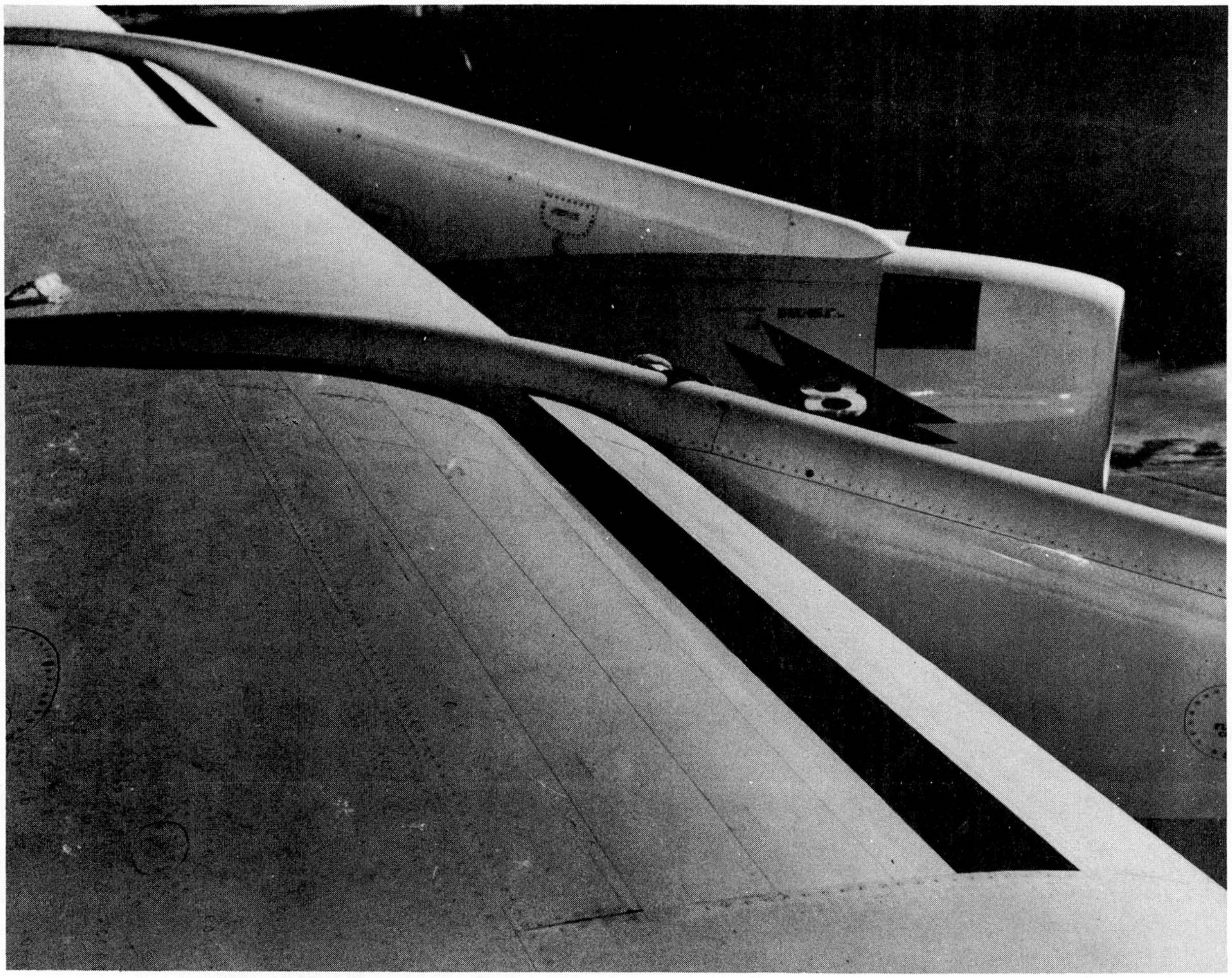

Fig. 7 DC-8 Wing Leading Edge Slots -
Initial Configuration

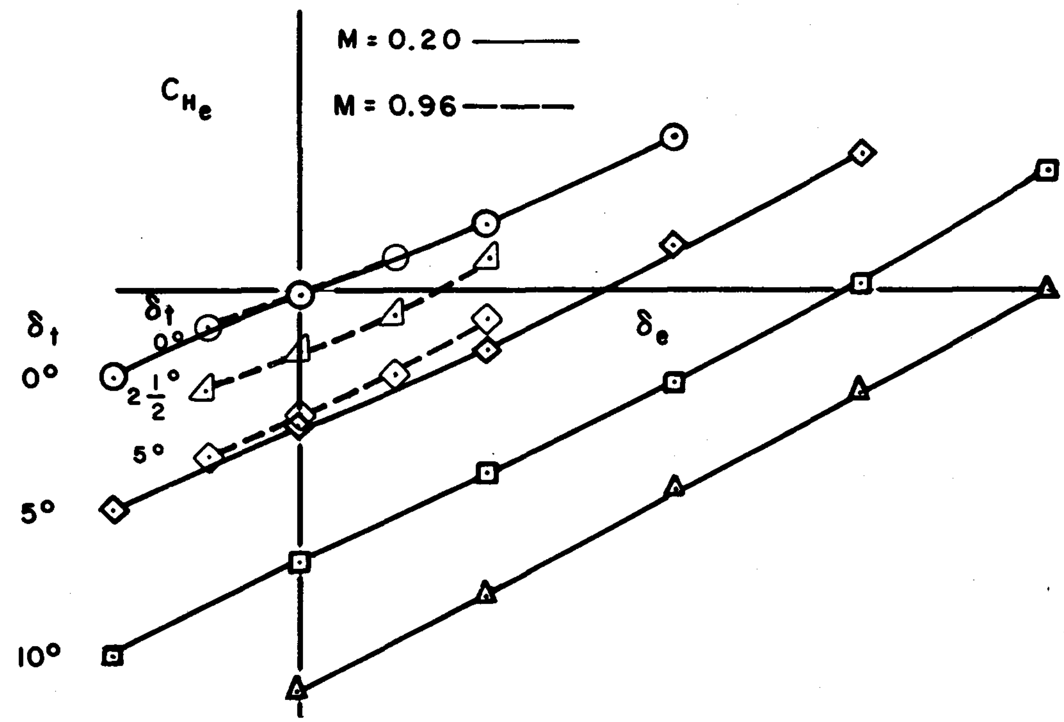

Fig. 8 DC-8 Elevator Hinge Moment Coefficients at Low and High Mach Number

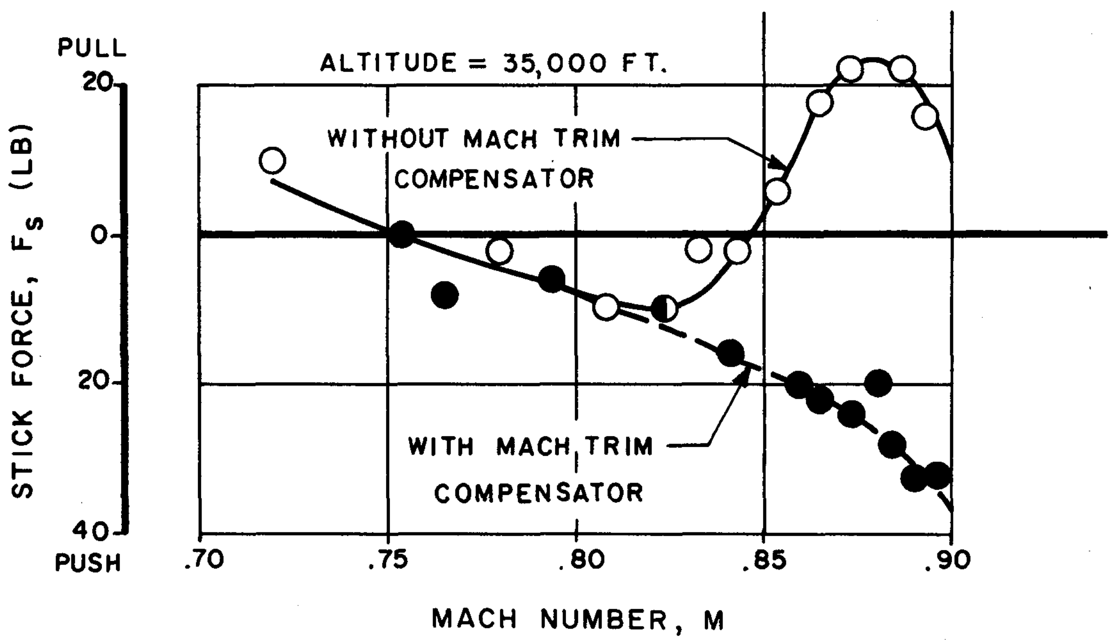

Fig. 9 Effect of DC-8 Mach Trim Compensator on Pilot Forces in the Transonic Tuck Region

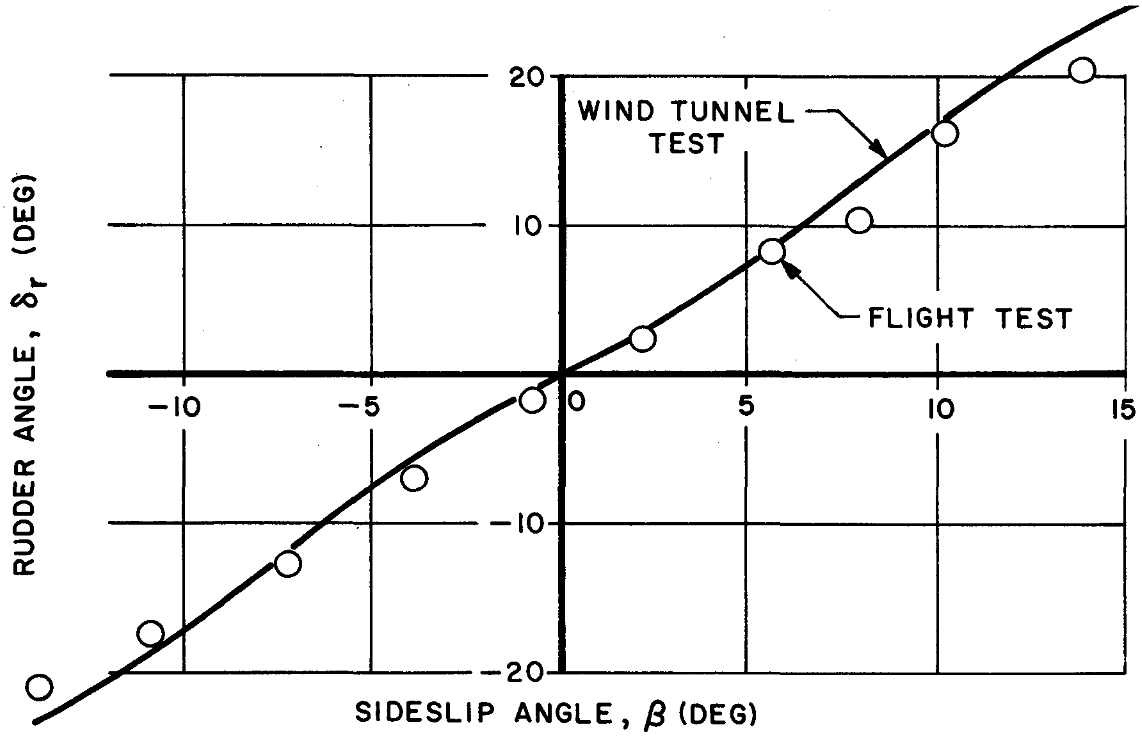

Fig. 10 Comparison of DC-8 Wind Tunnel and Flight Test Rudder Effectiveness in Sideslip - Landing Configuration

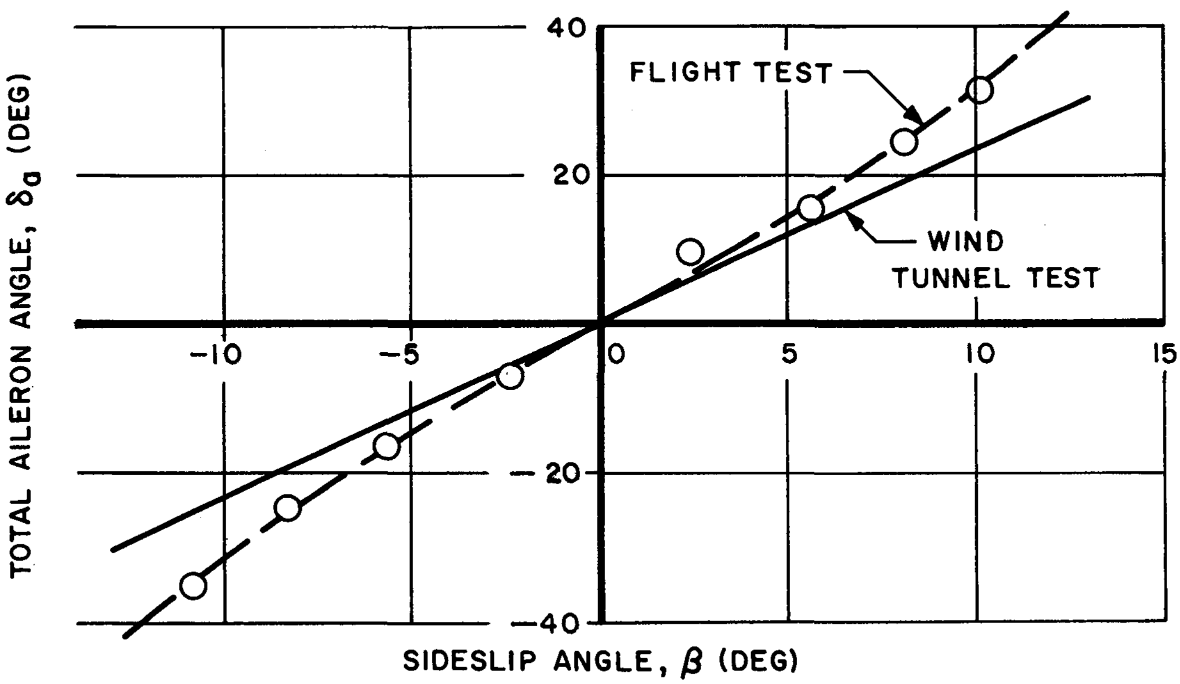

Fig. 11 Comparison of DC-8 Wind Tunnel and Flight Test Aileron Requirements in Landing Sideslips

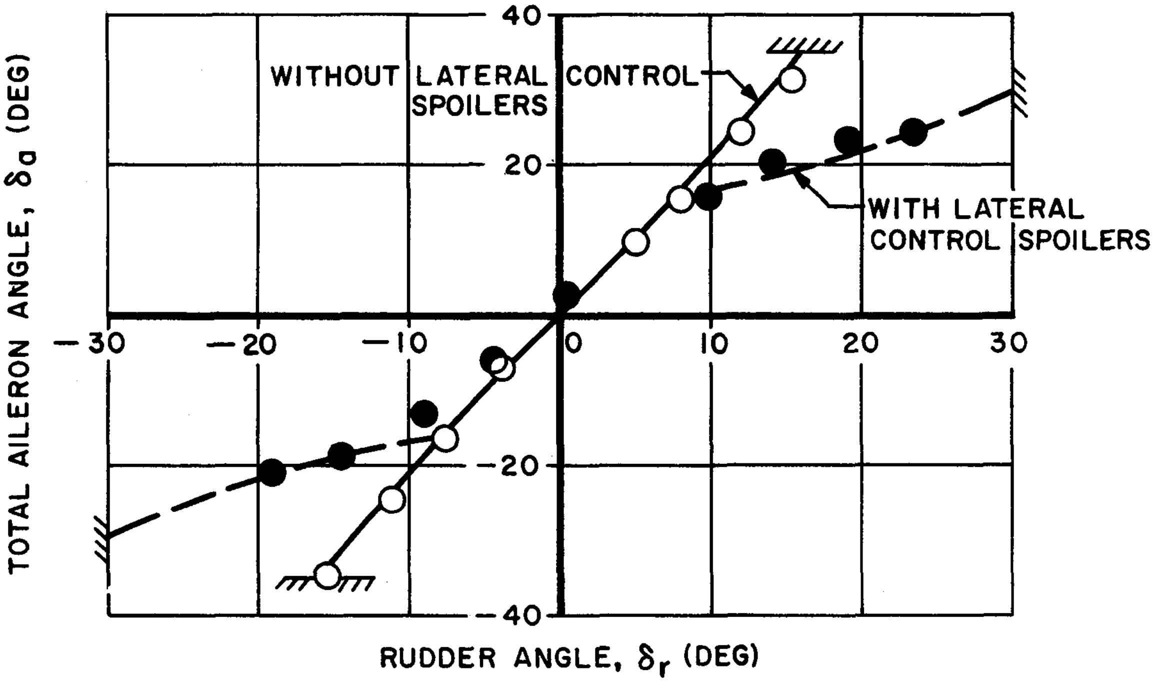

Fig. 12 Effect of DC-8 Lateral Control Spoilers on Aileron Requirements in Landing Sideslips

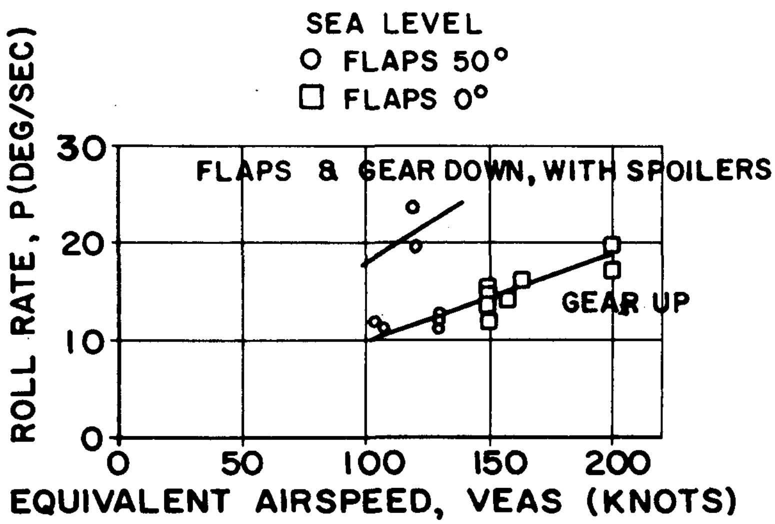

Fig. 13 DC-8 Low Speed Rolling Performance

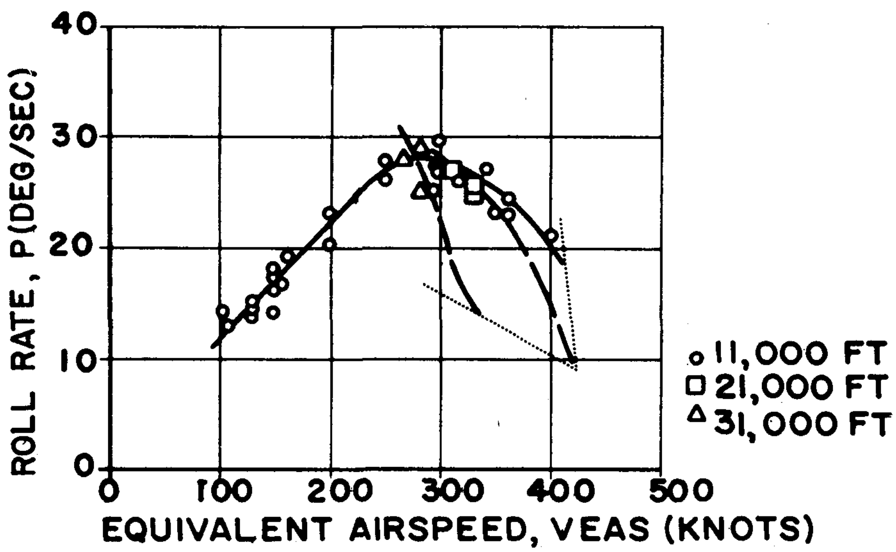

Fig. 14 DC-8 High Speed Rolling Performance

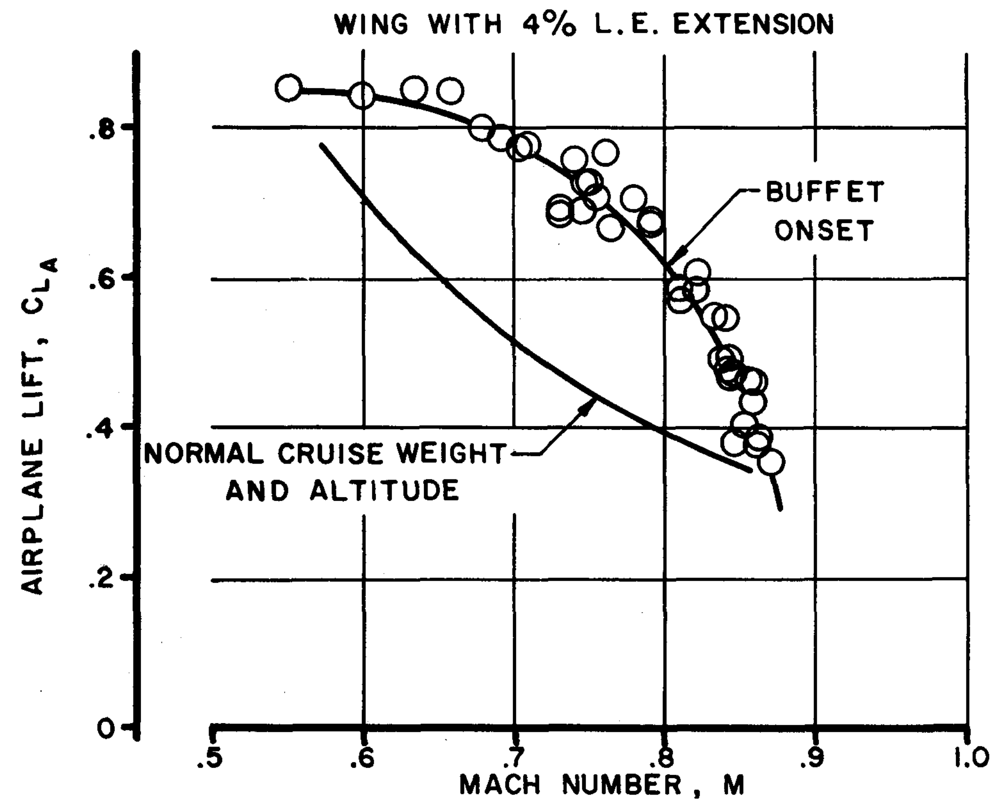

Fig. 15 DC-8 High Speed Buffet Boundary with Revised Wing Leading Edge

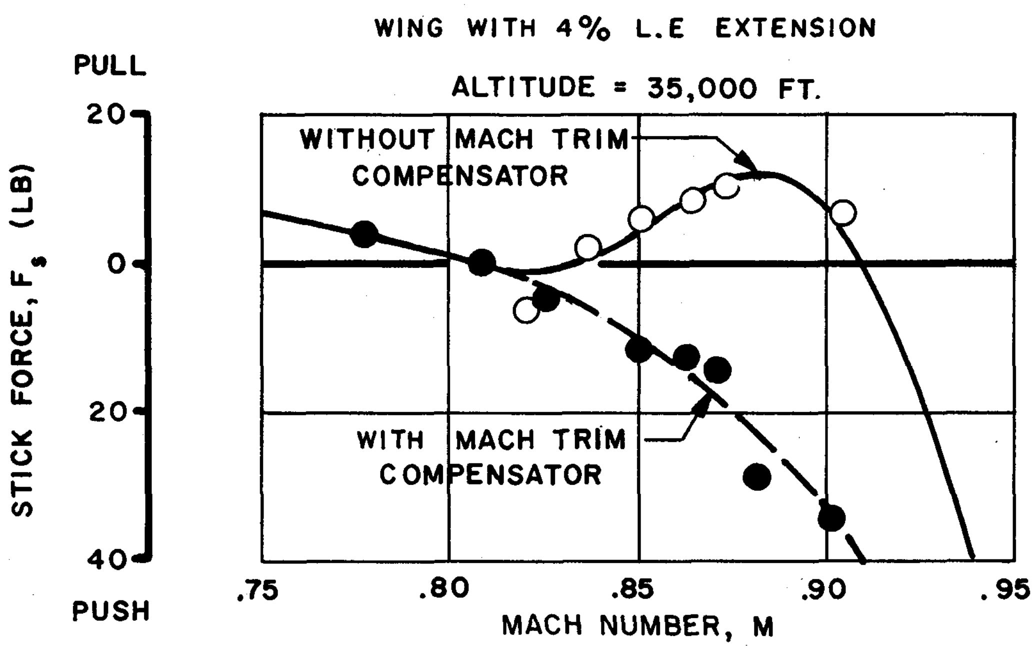

Fig. 16 DC-8 Transonic Tuck Pilot Force Characteristics with Revised Wing Leading Edge